Chapter 4. The Fermilab Complex as Injector

4.1 The Fermilab Complex and Beam Properties

The present Fermilab accelerator complex consists of a 750 keV ion source, a 400 MeV linac, the 8 GeV Booster, the 150 GeV Main Injector, and the 1 TeV Tevatron. The first three machines operate at 15 Hz; the Main Injector acceleration cycle to 150 GeV is approximately 2.4 seconds, and the superconducting Tevatron acceleration cycle is approximately 40 seconds. The Tevatron has a circumference of 6283 m, and has six long straight sections for injection and extraction. The F-0 straight section is used for the Tevatron RF and for injection from the Main Injector (for clockwise protons in the Tevatron). Figure 4.1 shows a schematic of the various machines.

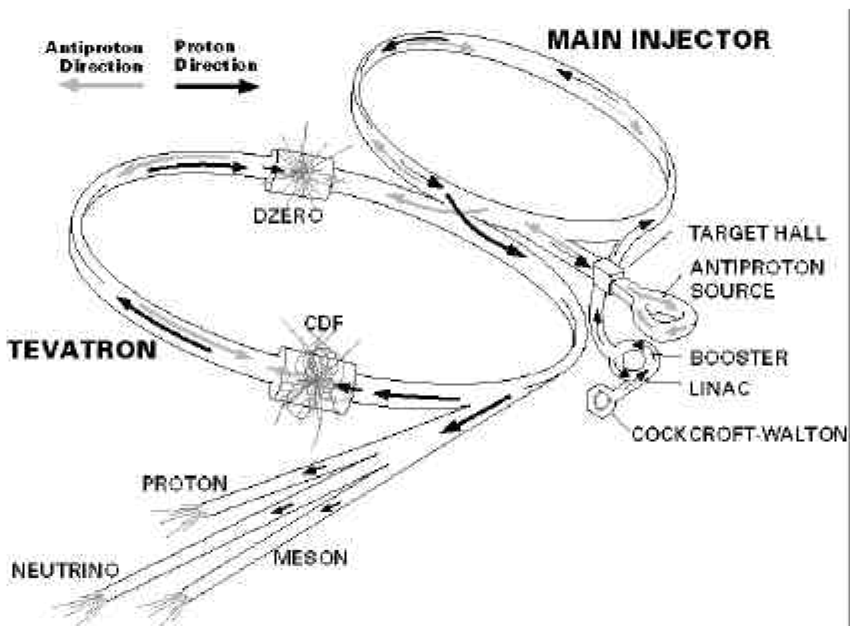

Figure 4.1. Schematic of the existing Fermilab accelerator complex..

The Fermilab accelerators produce beam of the desired emittances for use in the VLHC. In particular, the desired intensity per bunch is at the low end of what is demanded of the Booster by present operations, as shown in Figures 4.2 and 4.3. The questions related to preservation of these emittances through the Main Injector and the Tevatron will be addressed during the coming Collider run. Previous experience with the Main Ring as the injector to the Tevatron yielded transverse emittance dilutions of about 50-100%, but that also involved bunch coalescing to produce bunches of greater than 2×10^{11} protons. Careful attention and some possible upgrades will be required, but the emittances assumed in the Design Study represent reasonable projections from the current performance of the Fermilab injector.

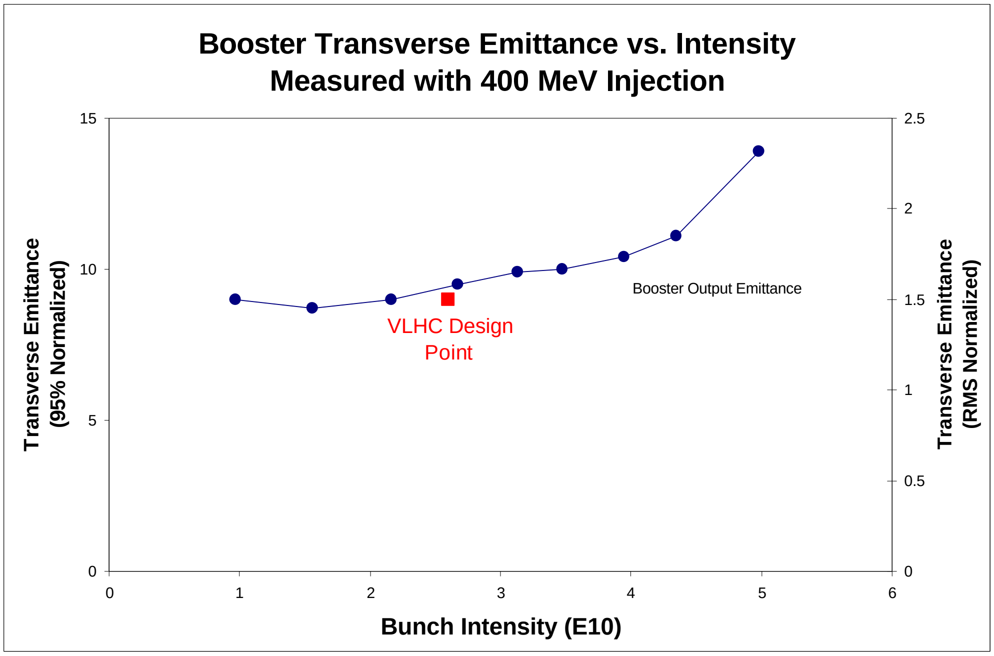

Figure 4.2. Measured transverse beam emittance (95%, normalized) delivered from the 8 GeV Booster as a function of beam intensity.

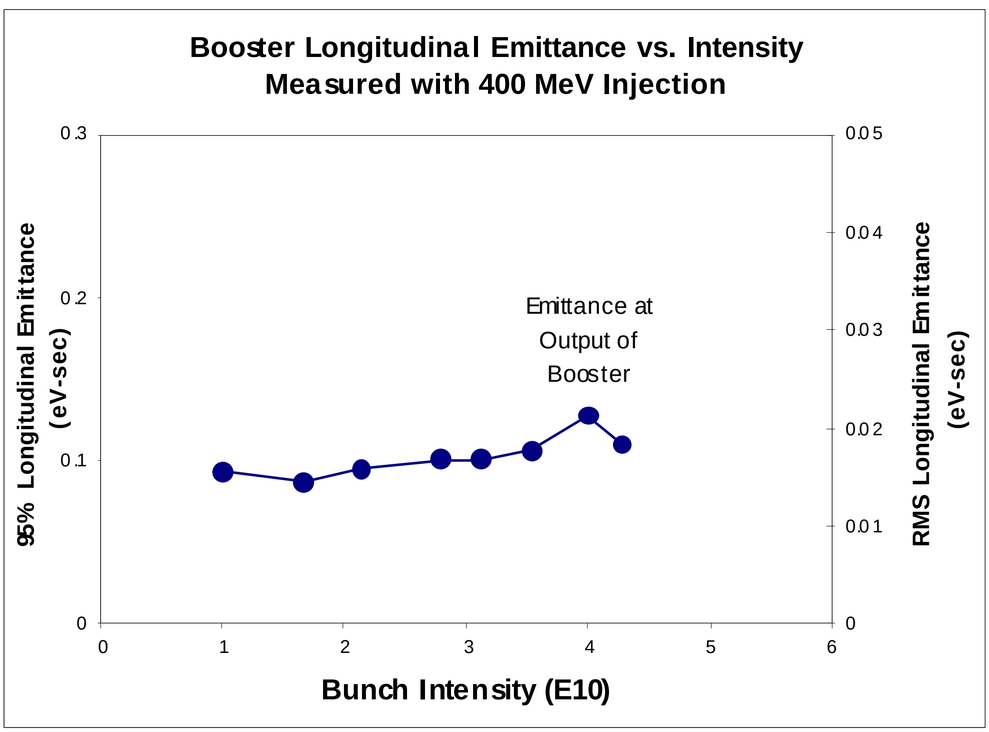

Figure 4.3. Measured longitudinal beam emittance delivered from the 8 GeV Booster as a function of beam intensity. The longitudinal emittance at collision of 0.4 eV-sec rms assumed in the VLHC Design Study allows for significant emittance dilution during acceleration and possible coalescing operations.

4.2 Operational Scenarios

The Booster, Main Injector and Tevatron all operate with 53-MHz RF systems, providing bunch spacings of 18.83 ns; the harmonic numbers are 84, 588 and 1113. These correspond to circumference ratios of 1:7:13.25. Due to the extraction kickers in the Booster, one to two buckets are lost at transfer time. Further, the requirement for kicker rise times in the Main Injector (for extraction and abort) implies that only about 6/7 of the circumference is filled, and within the section that is mainly filled, there are the small (two to three bucket) gaps resulting from the rise time for the injection kickers. Since the Main Injector is only about one-half the size of the Tevatron, two Main Injector cycles are needed to load the Tevatron. Here again, the rise time of the Tevatron injection kickers requires a gap between the two beam-fills.

The scenario used during the 1999 fixed target run involved one Main Injector cycle with five Booster batches, followed by a second cycle with six Booster batches. Assuming 82 bunches per batch, each Tevatron cycle will accelerate 82 x 11 bunches = 902 bunches. Interspersed between strings of filled buckets, there are nine gaps of ~two empty buckets each, and one large gap of about 50 buckets. Thus, the bunches span approximately 970 buckets, or 5.476 km. To fill both rings of a 233-km circumference machine requires 84 Tevatron acceleration cycles, or one hour. The actual number may be slightly smaller due to the injection kicker rise times in the VLHC, or one may choose to change the filling structure of the Tevatron from that described above, e.g. inject five batches each time, for a total of ten batches, rather than eleven, so that a more uniform bunch pattern is created.

To use the Tevatron as the injector for a much larger machine, the geometric relationships between the two rings will determine the transfer line orientations. Several options were considered, as discussed below. In two of these options, the Main Injector and Tevatron continue to operate as they do now, with new extraction area(s) needing to be installed. At the present time, both the Main Injector and the Tevatron only accelerate protons in one direction, clockwise in the Tevatron and counterclockwise in the Main Injector. In the third option, the Tevatron is converted to bipolar operation, where protons are accelerated clockwise on some cycles, and counterclockwise on others, by reversing the magnetic fields of the magnets. To convert either machine to bipolar operation is relatively straightforward. Reversing switches need to be installed in each power supply circuit. In the Tevatron, a second set of quench-bypass SCRs is required to conduct the current around the quenching magnets.

The main issues with bipolar vs. unipolar operation have to do with injection and extraction. For a bipolar Main Injector, a new transfer line needs to be built to inject clockwise protons. The civil construction for such a line may be minimal, but the details of injection into the Main Injector need to be developed. Transfer to the Tevatron would be accomplished through the existing A-1 beamline, presently used for antiproton injection into the Tevatron. A new abort for clockwise Main Injector protons would need to be constructed. This could be an internal abort, i.e. one which does not require civil construction, if there is no other physics program associated with the clockwise protons.

For a unipolar Main Injector but a bipolar Tevatron, a new transfer line is required. The most likely route is from MI-40 to the Tevatron E-0 straight section. This distance is fairly straight, but will require an enclosure approximately 1300 m long, together with focussing magnets, utilities, etc. The MI-40 region also contains the Main Injector abort dump; a channel has been provided in the dump to allow a future beam extraction though this area. Therefore, no demolition of the MI enclosure would be required during the civil construction of the beamline.

For bipolar operation of the Tevatron, a new abort is required for the counterclockwise protons. This may be an internal abort as presently used in collider operation.

4.3 Tevatron Extraction Lines

The placement of the extraction lines from the Tevatron to the VLHC will be driven by the requirements of the new machine. The VLHC orientation and elevation are determined by the geology of northern Illinois. This in turn determines the geometric relationship between the VLHC and the Tevatron, with the remaining degrees of freedom being the choice of the extraction straight section(s), the amount of bending in the transfer lines, and shifting the VLHC ring by distances on the order of one to two times the Tevatron radius.

The distance between the injection regions in the VLHC is 10,839 m to the outside ends. With the length of the utility straight section of 1000 m, then the length of each transfer line is approximately 4420 m. At a depth of 100 to 150 m below the Tevatron, the line has an average slope of 23 to 34 mrad, or 2.3 to 3.4 percent slope. This is below the upper limit of 4 percent for using wheeled-vehicles for magnet installation.

The transfer line will necessarily change from cut-and-fill construction in the glacial till above the bedrock (elevation approx. 690 feet) to tunneling in the dolomite. Passing through this interface will present significant construction challenges with respect to water inflows over an excavation that is several hundred feet long. Based on the experience of the NuMI construction presently underway, the construction of the beamline enclosure will have to deal with hundreds of gallons per minute of water at a minimum. If blasting is used to begin the excavation into the bedrock, this could easily become thousands of gallons per minute.

In the following sections, some of the various options for beam transfers between the Tevatron and the VLHC are discussed in more detail. At any point in which a beamline connects to the Tevatron, it should be assumed that the building over that straight section must be demolished and rebuilt, and that a new building will be required for access to the beamlines. In this regard, F-0, which is used for Tevatron injection from the Main Injector, should not be used; to use A-0 would be very expensive due to the need to demolish and reconstruct much of Transfer Hall and the Transfer Gallery. The presence of a large number of utilities in the vicinity of A-0 is a further complication. However, an extraction from A-0 only involving clockwise protons, in which the beam is first extracted in the direction of Switchyard, so that the actual civil construction does not disrupt the A-0 area, may be possible.

4.3.1 Option A: Unipolar Tevatron, Single Extraction Region

In this option the clockwise beam in the Tevatron is extracted at one straight section, and is then split into two lines, with a net bending of nearly 180°. See Figure 4.4.

This option has the following advantages. It involves only one connection to the Tevatron, and no technical changes to the Main Injector or Tevatron are required. It could be configured to have only one section of the line penetrating the till/bedrock interface. The disadvantage is a potentially longer tunnel overall, and the amount of bending required (this option requires approximately half a Tevatron’s worth of bend magnets). This scheme could be used at A-0 (as shown below), B-0, C-0, D-0 or E-0.

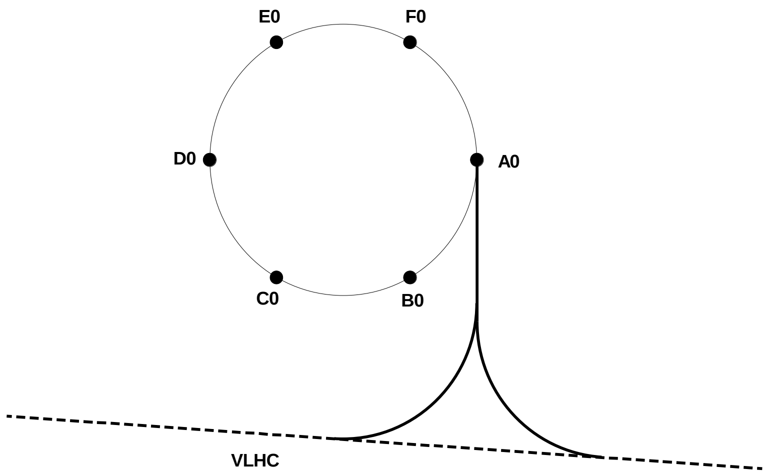

Figure 4.4. Unipolar Tevatron, single extraction line scheme.

4.3.2 Option B: Unipolar Tevatron, Two Transfer Lines

In this option, the clockwise beam in the Tevatron is extracted from two opposite straight sections, with a net bending of 20-30° in each of the two beamlines. This is shown schematically in Figure 4.5.

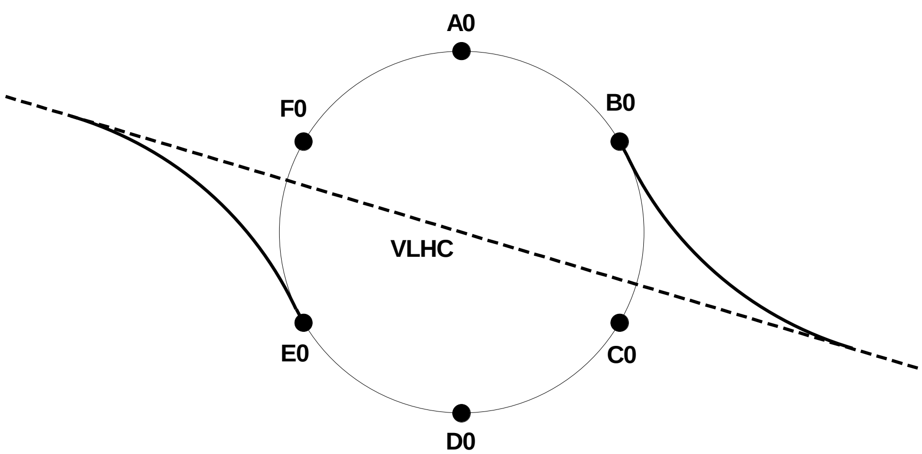

Figure 4.5. Unipolar Tevatron, two-extraction line scheme.

The advantage of this scheme is that no technical changes to the Main Injector or Tevatron are required. The disadvantages are that two separate beamlines must be constructed, each with a tie-in to the Tevatron, and a till/bedrock interface. Given the problems noted above regarding F-0 and A-0, this scheme best works for the combination of B-0 plus E-0, although A-0 plus D-0 is also possible. With additional bending, B-0 plus D-0, or C-0 plus E-0 could also be made to work.

4.3.3 Option C (Preferred): Bipolar Tevatron

In this option, both clockwise and counterclockwise beams in the Tevatron are extracted from the same straight section, with almost no bending required in the beamlines, although the exact geometry of the VLHC vs. the Tevatron may require some bending. This is shown schematically in Figure 4.6.

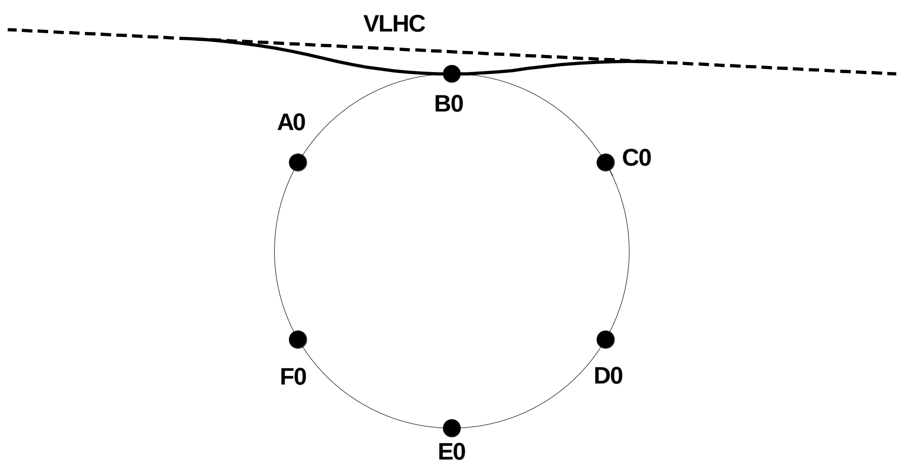

Figure 4.6. Bipolar Tevatron scheme. This option was chosen for the design study.

The advantages of the scheme are that a single tie-in to the Tevatron is required, and little bending is required in the beamlines. The disadvantages are that the Tevatron must be converted to bipolar operation, and the Main Injector either needs a new extraction line or must also be converted to bipolar operation with a new injection line; two till/bedrock interfaces are required for the Tevatron extraction lines. This scheme could be used at B-0, C-0, D-0 or E-0.

4.3.4 Extraction From the Tevatron

This section describes the requirements for Option A of the unipolar Tevatron scheme discussed above. For Option B, these requirements must be duplicated at two different areas. For Option C, the Lambertson magnets may be common, but all other aspects are duplicated. The discussion will be presented as occurring at the E-0 straight section, although it should be understood this can happen at B-0, C-0 or D-0 as well. In the following, it is assumed that the extraction is performed with horizontal kickers and Lambertson magnets which provide a mainly vertical deflection. If the reverse is required, a slightly larger total deflection is required to clear the Tevatron quadrupole at the end of the straight section.

Extraction of the clockwise protons is initiated by firing kicker magnets located at D-48. The kicker magnet and power supply system should be similar to the system presently installed at B-48 for the Tevatron abort. This is discussed in more detail below. The kickers deflect the beam across the septum of a series of Lambertson magnets in the E-0 straight section. Following the Lambertson magnets, one or more C-magnets provide additional downward bend. The various styles of existing Lambertson and C-magnets are detailed in the next section. As soon as sufficient vertical separation is achieved, it is extremely beneficial to add horizontal bending magnets to bend the extracted beam away from the Tevatron. The horizontal separation provided by this additional bending minimizes the amount of Tevatron enclosure which must be demolished and reconstructed during the civil construction.

The layout of the E-0 straight section is shown in Figure 4.7. In this figure, the magnets that are shaded black are the Tevatron quads; the magnets shaded gray are the ones required for Option A or B; the kickers at D-48 are not shown.

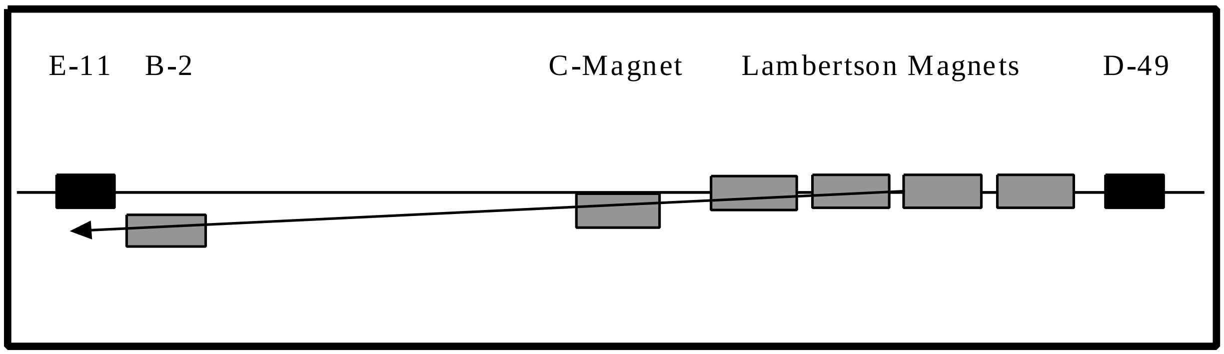

Figure 4.7. Tevatron extraction configuration for Options A or B viewed from radial outside.

Analysis of the required bending strength for the Lambertson magnets has been done. This is discussed further in Section 4.4. The two requirements are simply that the beam must be deflected enough to clear the quadrupole at the end of the straight section, but not so much as to run out of aperture within the Lambertson magnets themselves. The placement of the C-magnet has a similar constraint, in that it cannot be too close to the Tevatron beam pipe; something on the order of 75 mm of separation is needed between the circulating and the extracted beams.

For Option C, only the Main Injector Lambertsons have the required aperture in the bend plane to accommodate extraction in both directions. Since the 2-inch gap is not required, a new magnet with a 1-inch or smaller gap, but based on the MI design would probably be built. The magnet design must also be changed from the present symmetric design (with 7-in. above and below the field-free region) to an asymmetric design, with approximately 10-in. below. The extraction straight section for Option C is shown in Figure 4.8.

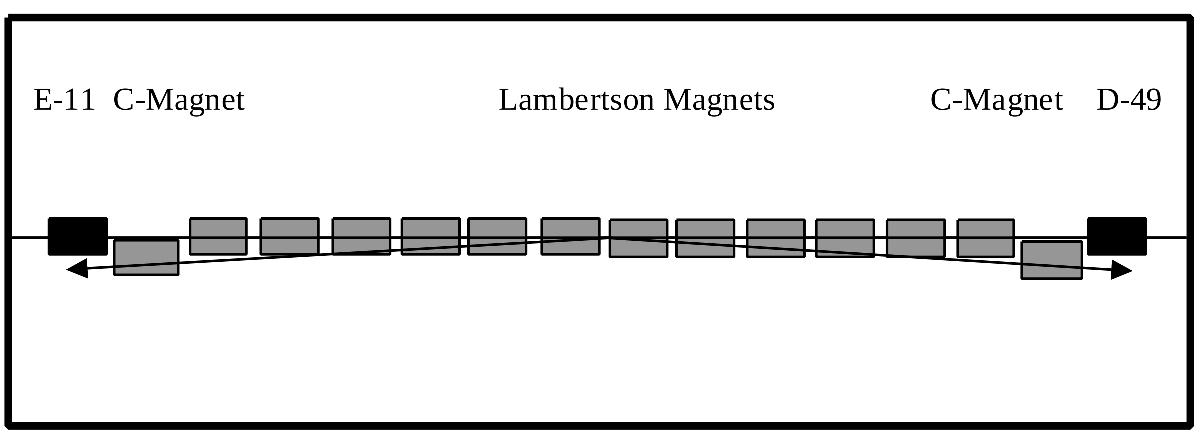

Figure 4.8. Tevatron extraction configuration for Option C.

4.3.5 Installation and Beamline Construction Issues Adjacent to the Tevatron

As mentioned above, providing some small amount of horizontal bending early in the transfer line is useful. This avoids the situation of having one beamline sloping down close to another beamline that is flat, and the resulting civil construction and installation difficulties that arise as a result.

Another issue is radiation from the Tevatron if it is desired to have access to the beamlines while the Tevatron is operating. While 20 feet of shielding is adequate above the Tevatron, muon production produces a forward plume in the plane of the Tevatron. Analysis done as part of the Main Injector project indicated that having 60 feet of radial shielding is adequate.

To facilitate the installation of long magnets, the minimum radius of curvature of any portion of the beamline between the access point and the VLHC ring has been set at 1000 m. This requirement does not pertain to the beamline enclosure in the immediate vicinity of the Tevatron in which shorter magnets will be placed. Thus, the outward horizontal bend mentioned above may wish to be cancelled by another bend to form a tight S-curve.

For magnet installation into the beamline or into the VLHC itself, an access ramp needs to be provided. Here it is assumed that this ramp begins at or near grade level and the installation ramp merges with the beamline enclosure above the dolomite. The portion of the beamline between the Tevatron and the installation ramp would need to be filled with shielding material if the Tevatron is operational during the installation phase. The portion between the surface and the beamline would need to be filled with some amount of shielding once the beamline becomes operational. For ease of reconfiguration, this material may be placed on rollers.

4.4 Transfer Line Magnets and Kickers

In Table 4.1, a combination of existing Fermilab magnet types is shown which meets the requirements for Options A or B; a similar table for Option C exists. Even with twelve MI-style Lambertsons, plus one C-magnet, the beam just clears the quad at the end of the straight section. However, the MI Lambertsons could also be pushed slightly higher in strength.

Table 4.1. Possible set of Lambertson and C-magnets for Tevatron extraction for Option A or B.

Magnet Type	Begin	Exit	Bend Center	Angle from Magnet	Angle at Exit	Deflection at Exit
Sym. TeV Extraction	0	5.68	2.8	0.00182	0.00182	0.005
Sym. TeV Extraction	5.68	11.4	8.5	0.00182	0.00365	0.021
Sym. TeV Extraction	11.4	17.0	14.2	0.00182	0.00547	0.047
Assym. TeV Extraction	17.0	22.7	19.9	0.00246	0.00793	0.085
TeV Abort C-magnet	22.7	26.6	24.6	0.00142	0.00935	0.118
End of Staight Section		51.3				0.350

The kicker magnets for Tevatron extraction should be fairly straightforward. The strength and rise time requirements should be the same as the existing B-48 abort kickers. The flatness over the extraction time of 20 μsec may need to be improved, however. Also, the existing kickers are vertical, whereas horizontal kickers are required in the scenarios discussed above.